COAL DESULFURIZATION BY MAGNETIC FORCES

S.C. Trindade*, J.B. Howard, H.H. Kolm, and G.J. Powers

Department of Chemical Engineering and Francis Bitter National Magnet Laboratory
Massachusetts Institute of Technology, Cambridge, Massachusetts

INTRODUCTION

Magnetic cleaning of coals has been studied in the past[1] by passing coal particles - usually pre-treated - suspended in air streams through conventional magnetic separators. The work reported here[2] is a systematic attempt at using high gradient magnetic separation techniques in coal slurries[3].

OBJECTIVES

There is a worldwide demand for new coal cleaning processes. This demand stems from the following: (i) upgrading of local coal reserves, mainly in developing countries; (ii) air pollution abatement, mostly of SO_2 and fly ash, in developed countries (the U.S. in particular); and (iii) preparation of raw materials for coal gasification and liquefaction, mainly in the United States. In response to this demand the work described here was conducted with the following objectives:

(i) Determine the technical and economic feasibility of using magnetic technology in coal cleaning. Brazilian coal from the Sideropolis field (30% mineral matter and 2-3% sulfur mainly pyritic) was used as a case example.

(ii) Study the fundamental principles of magnetic separation.

*Speaker, Present Address: Arthur D. Little Limitada, Rua Macedo Sobrinho, 48-ZC-02, Caixa Postal 9041, Rio de Janeiro, GB, Brasil.

PRINCIPLES OF MAGNETIC DESULFURIZATION OF COAL SLURRIES

The rationale for magnetic removal of minerals from coal is based on the magnetic susceptibility of its components. In 10^{-6} CGS units, the values are: organic material, -0.4 to -0.8; shales, 39 to 45; kaolins, 20 to 39; sulfides, 0.3 to 120; carbonates, -0.4 to 100; chlorides, -0.9 to -1.3; accessory minerals, of minor importance, -1.2 to 20. These values indicate a limitation on the removable amounts, for not all of the minerals are paramagnetic. Unfortunately, in many coals the minerals are intimately mixed with the coal substance, and grinding to fine sizes is the required prior to separation in order to maximize differences in magnetic susceptibility. In coal cleaning we are usually dealing with the removal of paramagnetics (pyrites and a fraction of the other minerals) from the coal matter (largely diamagnetic).

The translational force - attractive or repulsive - along a given direction on a small particle of a non-ferromagnetic material immersed in a magnetic field is given by

$$F_m = \chi .V.H\ (dH/dx) \qquad (1)$$

where F_m is the magnetic force acting on the particle in the x direction,

χ is the volume susceptibility of the particle, V is the particle volume, χ V is magnetization, and H is the total magnetic field acting on the particle in the x direction. The relatively recent availability of much larger magnetic fields and field gradients has permitted extension of use of magnetic separation beyond highly magnetic materials, i.e., ferromagnetics, to mixtures of paramagnetic and diamagnetic substances.

The basic principle of magnetic separation is then the development of a magnetic force - attractive or repulsive - as particles with different susceptibilities enter the reach of a magnetic field. Depending upon the geometry and the design of the separator, and the nature of the medium carrying the particles to be separated, forces arise - particle weight, buoyancy, and drag by the fluid carrying the particles, etc. - which oppose the separation

Inspection of Equation 1 suggests the important magnetic characteristics which a separator design should provide, namely an intense field strength and a large field gradient. Both should cover the largest possible volume to increase the capacity of the separator.

Consider a separator which consists of a packed column, inserted vertically in the bore of a solenoid magnet. The packing, a filamentary ferromagnetic material (stainless steel wool or a steel wire screen), is the source of the field gradient and holds magnetically captured particles. Our simplified model considers an isolated strand of steel wool taken as a cylindrical wire of uniform cross section (e.g. 100μ in diameter), inserted horizontally in a volume (e.g. the bore of a Bitter solenoid magnet), where the magnet field is uniformly verticle. The pyrite particles - ranging in size from 0 to 600μ - are carried in the water slurry flowing past the strand. The capture of a pyrite particle by the strand depends on the ratio R of the magnetic force to the opposing forces (net weight, W, and the hydrodynamic drag force, F_d) acting on the particle :

$$R = \frac{Fm}{W + F_d} = \frac{\chi\, VH\, (dh/dx)}{W + F_d} \qquad (2)$$

The expression for the magnetic force depends on the applied field, the magnetic properties of the materials, and the system geometry. It is, in all cases, a function of the center-to-center distance between the particle and the magnetized strand, and of the angular position of the particle with respect to the strand. The expression for F_d varies with the flow regime, i.e. with the particle Reynolds number, and also with the particle shape. The net weight depends on the volume of the particle, its density and the density of the liquid.

A mathematical model based on the above forces was developed to simulate the effect of the principal independent variables on the probability of capture of mineral particles, as measured by the value of R. The magnetic field was 20 kOe, the source of field gradient was a cylindrical steel strand of 100 microns in diameter, and only pyrite particles (susceptibility equal to 25×10^{-6} emu/gm) were considered.

Figure 1 shows the effect of particle size on R for different slurry velocities (V_s). The curves indicate that there is an optimum particle size for which the probability of capture reaches a maximum. The effect of the slurry velocity is shown by the flattening of the curves as the velocity increases. In all cases the drag force predominates over the magnetic force for small particles where the particle weight is negligible. For large sizes the net weight is the most important force. For intermediate sizes the magnetic force is relatively more important.

APPARATUS AND PROCEDURES

The schematic of the apparatus used in this work is shown in Figure 2 and described elsewhere[3]. Pre-washed coal - 25.4 to 0.6 mm top size - was ground to 0.42 to 0.044 mm top size. Slurries were prepared by mixing known amounts of coal, of known size distribution, water, and for the finer sizes, a wetting agent. The slurry was passed once through the separator, essentially a packed column inserted in the bore of a solenoid magnet. The packing consisted of magnetic stainless steel wool or screens at packing densities ranging between 1 and 13 volume percent. The materials retained (mags), and the materials passed through (tails) were analyzed for total ash content and sulfur. Organic sulfur was estimated by the differences between total sulfur and pyritic plus sulfate sulfur. In a few cases the magnetizations of the coal minerals in the original coal, tails and mags were measured. Recoveries (total, ash, sulfur, etc.) are always defined with respect to the total amounts present in the original coal.

EXPERIMENTAL RESULTS

Evidence of Magnetic Separation

The magnetization curves of the coal minerals in the products of magnetic separation provide evidence of magnetic action. The coal minerals were obtained by low temperature ashing (LTA), in which the coal substance is slowly combusted at 150 C, leaving behind the unaltered minerals[4]. The measurements employed Foner's vibrating-sample magnetometer[5]. As shown in Figure 3 at a field of 15 kOe the magnetization of the LTA of the "tails" is 30 times smaller than the LTA of the "mags", indicating the removal of minerals with higher susceptibility from the original coal and their concentration in the "mags".

Typical Result

A typical result of a laboratory test of magnetic separation of coal is shown below. The void volume of the packing was 95%, the field intensity was 20 kOe, the slurry concentration was 2.5%, the top particle size was 44 microns and the slurry velocity was 2.0 cm/sec. The recovered product constituted 80% of the feed and contained only 0.81% sulfur as opposed to 1.32% sulfur in the feed. In a practical situation the "mags" could be further processed to improve the product yield.

FEED	BASE	=	100	
			27. %	Ash
			1.32 %	Total Sulfur
			0.66 %	Pyritic Sulfur
TAILS	RECOVERY	=	80.8	
			24. %	Ash
			0.81 %	Total Sulfur
			0.24 %	Pyritic Sulfur
MAGS	RECOVERY	=	14.4	
			38.9 %	Ash
			2.52 %	Total Sulfur
			2.01 %	Pyritic Sulfur

Effect of the Independent Variables

The experimental results confirmed the force balance model with respect to the effects of particle size and slurry velocity. One of the important predictions of the model is that there should be a given particle size for which R reaches a maximum. Consequently we would expect that the sulfur concentration, and the sulfur recovery in the mags would peak at the same diameter, if pyrites are the dominant form of sulfur, and if they are sufficiently liberated.

In a series of runs coal was sieved to produce narrow particle size distributions which gave approximately monodisperse slurries when suspended in water. The following size ranges were obtained: (i) below 44μ, (ii) 44-53μ, (iii) 53-63μ, (iv) 63-74μ, (v) 74-105μ, (vi) 105-177μ, and (vii) 177-420μ. Steel screens were used as packing (91% void). The slurry concentration was 2.6 gm/100 ml and the linear velocity ranged between 2.3 and 2.6 cm/sec. The applied magnetic field was kept constant at 20 kOe. Figure 4 shows the effect of particle size on sulfur recovery in mags.

Analysis of the forms of sulfur for the maximum point showed that pyritic sulfur accounted for most of the total sulfur in mags.

According to the model, R should decrease as the slurry velocity increases. Consequently "mags" recovery should decrease, sulfur concentration in the mags should increase because the particles of higher susceptibility (pyrites) should constitute a majority of those retained. All these predictions were confirmed experimentally.

ECONOMIC ANALYSIS

A practical scheme of magnetic separation applied to coal beneficiation would be based upon the same concepts described here but the operation would be carried out in large capacity continuous equipment. In one possible situation the separator packing would move in and out of a magnetic field region to allow for continuous washing of the packing to remove trapped materials. The slurry fed to the separator would always find a clean packing. A continuous device of this type has been developed for use in beneficiating taconite ore which resembles, geometrically, a 'carousel' slide projector.

Table 1 summarizes the results of a preliminary economic analysis of a magnetic separator for coal cleaning, based on experimental results. Top particle size was 28 mesh, field intensity was 20 kOe and slurry velocity was 4.0 cm/sec in a once through operation. We tested the sensitivity of the processing costs to changes in the cost of power, depreciation time, etc. The estimated processing costs fell into a range of 30 to 63 cents per ton of coal produced. This range compares favorably with conventional beneficiation techniques.

TABLE I

COSTS OF MAGNETIC DESULFURIZATION OF COALS

Typical Case

field	20 kOe
size distribution	28 mesh x 0
once through operation	

	Feed (=100)	Product (tails) (=72)
Ash %	30.1	27.9
Sulfur %	1.80	1.80

Plant Characteristics

	Base Case	Alternatives
Investment, 10^3 \$	6480	6480 - 12960
Operational Capacity, 10^3 t/yr	7920	2640 - 7920
Number of units (3.6 m^2 each)	8	8 - 16
Depreciation time, yrs	20	10 - 20
Power costs, mills/kwhr	10	10 - 20

Processing Costs, cents/ton coal FOB Plant

	Base Case	Alternatives
Indirect Costs	9.2	9.2 - 27.9
Direct Costs	12.5	12.5 - 18.9
Total Costs		
Coal Fed	21.7	25.8 - 45.5
Coal Produced	30.1	35.8 - 63.2

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions of this study are summarized below.

- The magnetic cleaning of coals can remove practically all the liberated pyritic sulfur and a portion of the other minerals.
- The experimental results can be predicted or interpreted, at least qualitatively, by the proposed model.
- The experimental work has confirmed the importance of the key independent variables: particle size and liberation; slurry velocity; field intensity and packing characteristics.

With regard to the process economics, the following points are important:

- magnetic separation is a capital intensive operation;
- without superconducting magnets the operation is sensitive to the cost of power;
- grinding costs were not included because, although fine grinding increases liberation, the probability of magnetic capture is diminished, according to the model;
- the process looks commercially feasible.

Recommendations for future research include:

- enhancement of the susceptibility of the materials to be separated, probably by changes in the nature of the particle surface;
- study of additional coals to characterize their behavior;
- study of the capacity and performance of systems of separators with mags recycle;
- coupling of magnetic separation with conventional coal cleaning schemes;
- use of air laden with coal;
- fundamental studies including:
  - magnetic separation visualization
  - use of systems simpler than coal slurries

- magneto-chemistry of the pyrite system
- quantitative modelling, i.e. development of a magnetic adsorption theory

ACKNOWLEDGEMENTS

One of the authors (S.C.T.) was supported by the Conselho Nacional de Pesquisas of Brazil during this research.

REFERENCES

1. Ergun, S. and Bean, E.H., "Magnetic Separation of Pyrite from Coals", Report of Investigation No. 7181, U.S. Bureau of Mines, Pittsburgh, 1968.

2. Trindade, S.C., "Studies on the Magnetic Demineralization of Coals", Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1973.

3. Kolm, H.H., Maxwell, E., Oberteuffer, J.A., Kelland, D.R., DeLatour, C., and Marston, E.P., "High Intensity Magnetic Filtration", 17th Annual Conference on Magnetism and Magnetic Materials, API, IEEE, AIME, ONR, and ASTM, Chicago, 1971.

4. Estep, P.A., Kovach, J.J., and Carr, C., Jr., Anal. Chem. 1968, 40(2), 358-363.

5. Foner, S. Rev. Sci. Instr. 1959, 30(7), 548.

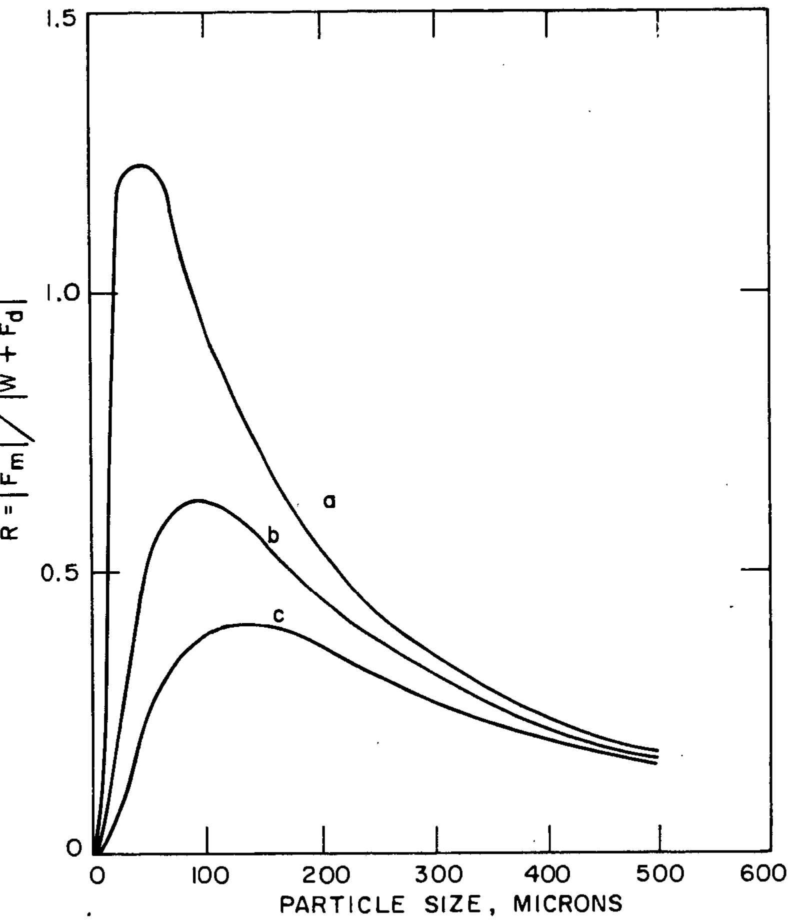
CAPTIONS TO ILLUSTRATIONS

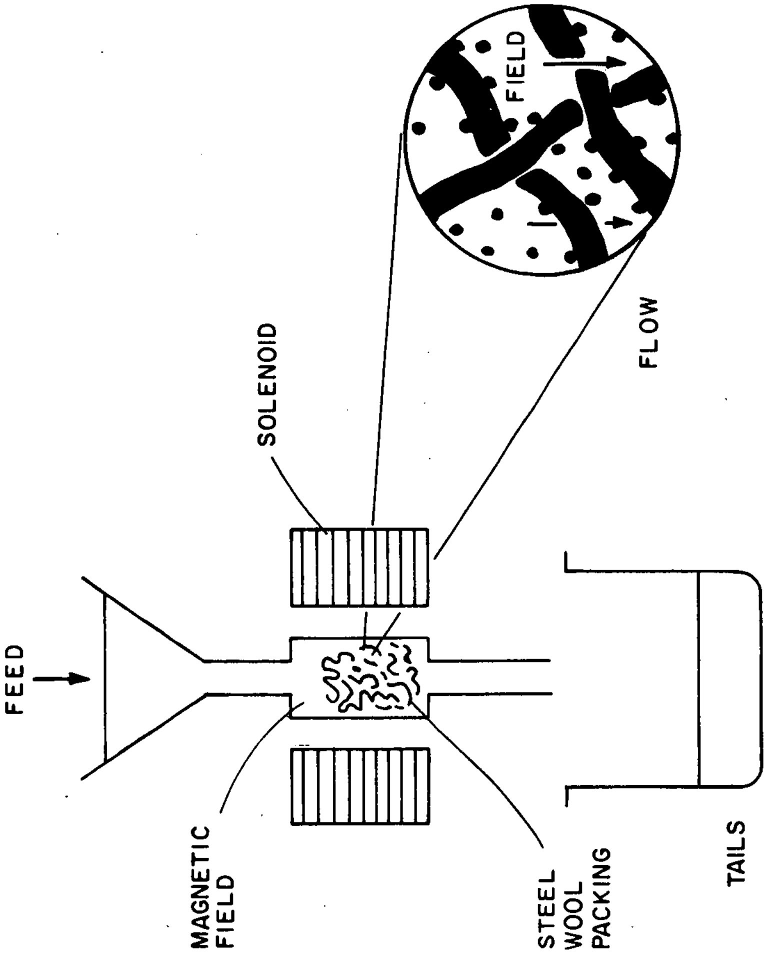
Figure 1. Effect of particle size and slurry velocity on ratio of magnetic force to drag force plus net particle weight as indicated by simple model (slurry velocity, cm/sec: (a) 0.1; (b) 1.0; (c) 2.0)

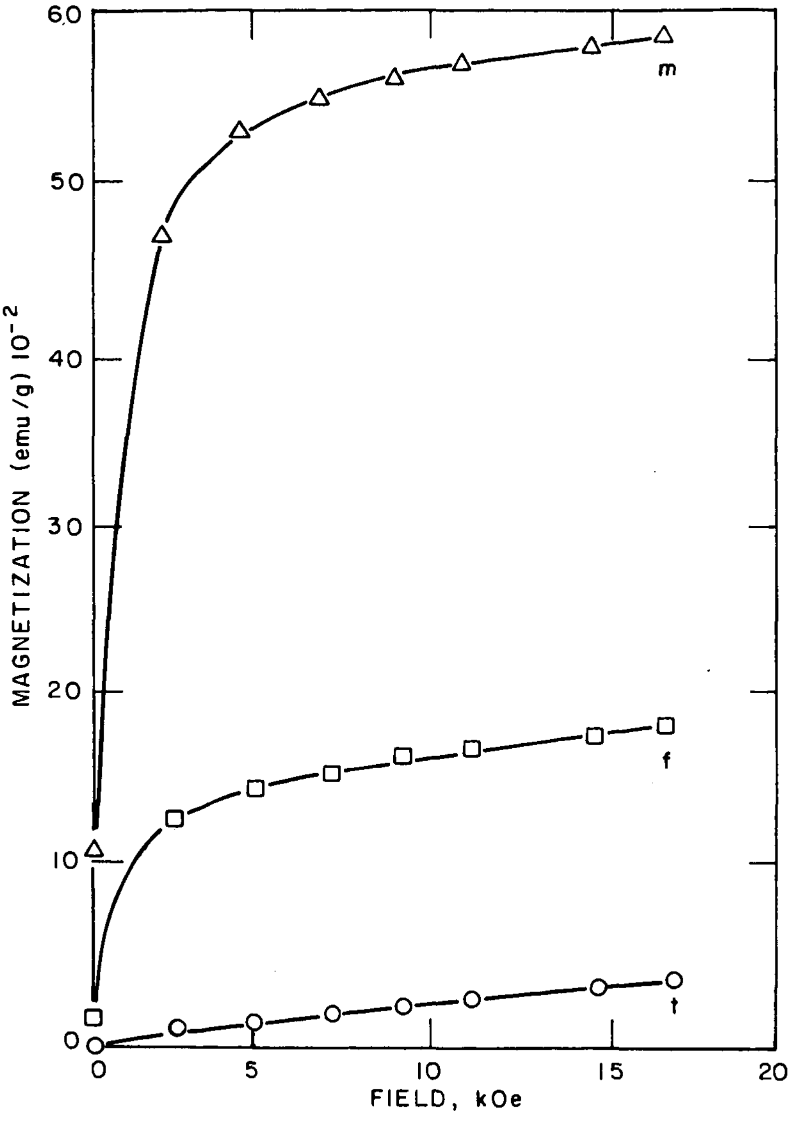
Figure 2. Schematic Arrangement of Equipment

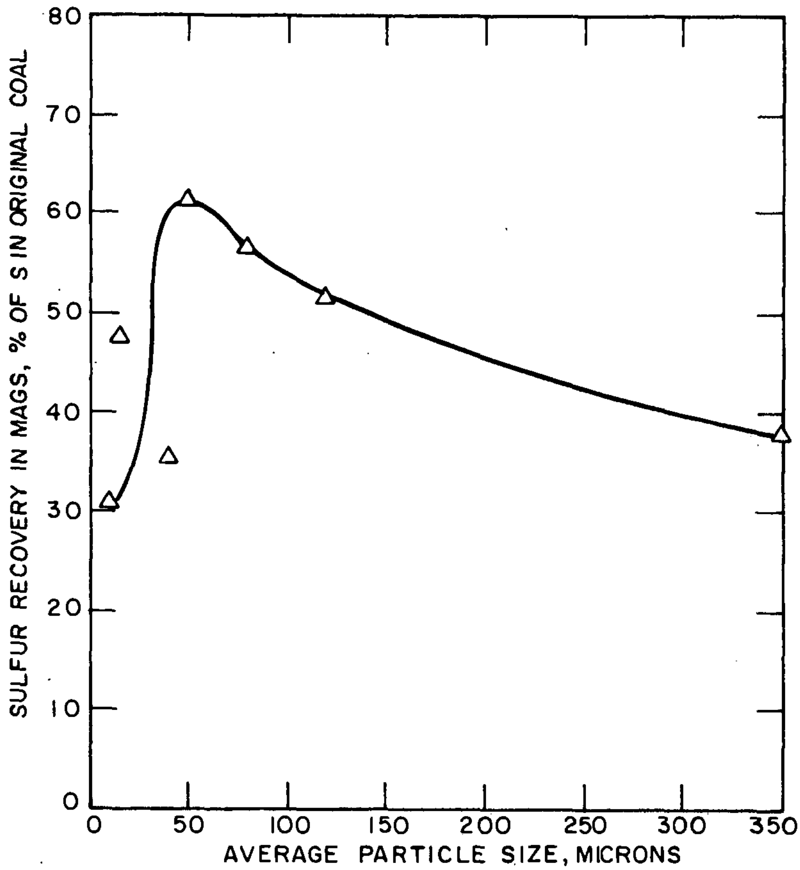
Figure 3. Observed effect of magnetic field on magnetization (m, mags; f, feed; t, tails)

Figure 4. Observed effect of particle size on sulfur recovery in mags


1.5
1.0
0.5
0
$R = |F_m| / |W + F_d|$
a
b
c
0
100
200
300
400
500
600
PARTICLE SIZE, MICRONS


FEED
SOLENOID
FIELD
FLOW
MAGNETIC
FIELD
STEEL
WOOL
PACKING
TAILS


MAGNETIZATION (emu/g) 10^{-2}
60
50
40
30
20
10
0
0
5
10
15
20
FIELD, kOe
m
f
t



80
70
60
50
40
30
20
10
0
SULFUR RECOVERY IN MAGS, % OF S IN ORIGINAL COAL
0
50
100
150
200
250
300
350
AVERAGE PARTICLE SIZE, MICRONS